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The occurrence and effects of wave impacts

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The determination of design parameters for coastal structures has historically often involved the definition of maximum water levels, the highest significant wave height and the longest wave periods. The design then proceeds with these values using numerical models, direct design methods or physical model studies. Design studies have often been conducted with maximum water levels, using random seas with previously determined parameters, a chosen wave spectrum and a sufficiently large number of waves. Parametric analysis methods using multiple parameters have identified that different combinations of water level; wave condition; perhaps fluvial discharge; or sea bed condition; may all influence the response. Recent research into the most important responses of vertical structures (plunging wave impact, toe scouring, overtopping and overtopping-induced loading) indicates that these mechanisms are all linked to the occurrence of violent wave impacts. Wave breaking is a depth-limited phenomenon, with plunging breakers occurring only for a limited range of wave height to water depth ratios. For given storm wave heights, but tidally varying water levels, this wave-breaking regime will often only prevail for a limited amount of time, leading to the conclusion that the duration of maximum exposure, namely the length of time that a coastal structure is exposed to the most important wave-induced damage mechanisms, is a function of the combined probability of (at least) water level (tidal + storm surge) and wave height/storm profile characteristics. This may have significant consequences for the definition of critical design parameters and the parameter variations employed in model tests.

1. INTRODUCTION

Many vertical coastal structures such as seawalls and vertical breakwaters are exposed to violent wave action during storm events, in which the main forms of wave-induced exposure can be classified as listed here.

(*a*) Direct wave impact loads and their less direct consequences (pressure propagation into joints and fissures).
(*b*) Toe scouring: the wave-induced formation of a scour hole at the toe of a structure.
(*c*) Overtopping: water masses thrown over the crest of the structure by wave action.
(*d*) Vertical impact of water masses: pressures generated by down-falling water from wave overtopping.

Figure 1 illustrates these wave effects on a coastal structure. Since all these forms of exposure to violent wave action are stochastic, the duration of exposure will strongly influence the magnitude of the maximum response.

Direct wave impacts, vertical (downfall) pressures and toe scour affect the stability/integrity of the structure, whereas overtopping will affect its functionality (by preventing access, creating hazards for users, inducing waves inside a harbour, etc.). The design recommendations for three exposure types have recently been improved[1,2] whereas recommendations for toe scour are still under development. In the context of vertical composite breakwaters, seaward loading that is a result of wave overtopping and downfall as well as impact-induced uplift pressures can affect the stability of the structure.[1,3] These mechanisms are also linked to breaking wave impact but will not be considered further in this paper.

Common practice for the determination of design conditions has historically often been to assume the highest water level (astronomical tide plus surge plus sea level rise) as being critical, and then to determine a maximum (significant) wave height for a given return period assuming that the highest wave generates the most critical conditions. The four critical conditions listed above and their effect on the design and performance of a structure are then considered more or less individually. Even if there is a high probability that the maximum water depth and wave height/period will occur together, the assumption that the maximum response/exposure will occur for that condition may not necessarily be correct, as this paper will demonstrate.

For more important structures, physical model tests—mostly employing random seas with spectra appropriate to the location of a structure and with a specified number of waves (usually 500 to 1000)—are conducted to determine key responses such as wave pressures or overtopping rates. Again, and in accordance with the design philosophy stated above, the focus has often been on maximum water levels and wave heights. Only occasionally are lower water levels investigated, sometimes leading to surprising results. An investigation of overtopping on an S-shaped revetment on Norderney Island, Germany was conducted to assess the effectiveness of a proposed wave return wall.[4] The

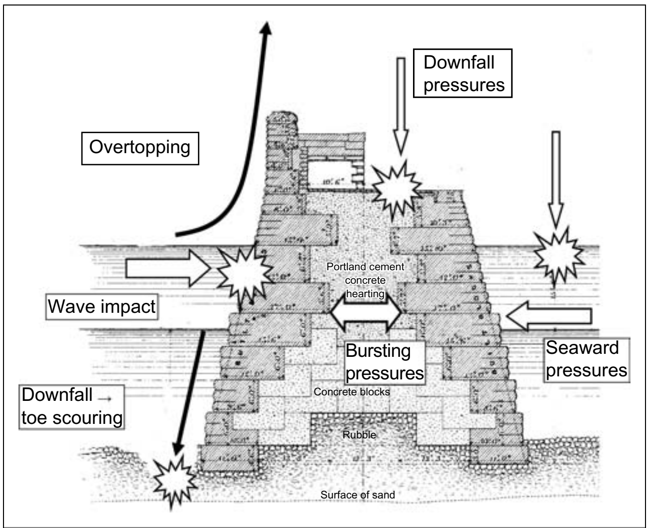

Fig. 1. Wave effects on a coastal structure


(a)
(b)
Fig. 2. Different exposure conditions: Lomener Breakwater (Brittany): (a) mid-tide (© V. Hache, with permission); (b) high-tide (© J.-M. Sinquin, http://www.photosjeanmarc.info/index.html, with permission)

results indicated that for increasing freeboard and constant wave heights, the overtopping volumes for a lower mean water level (MWL) exceeded those for design water level significantly. This was attributed to waves breaking onto the revetment at lower water levels, leading to a high shoreward velocity and waves actually 'jumping' over the revetment.

In the context of toe scour, it is currently assumed that maximum scour occurs during the peak of the storm, but that the receding storm tends to refill the scour hole, explaining why—although many structures fail due to scouring—any actual evidence of scour holes is rare.[5]

In this paper, the authors present the argument for a different approach to determining the exposure duration or probability for vertical coastal structures. Based on the synthesis of recent research results, exposure duration or probability will be linked to the combined probabilities of storm wave heights and water level variations rather than to the maximum values of either. The conclusions from this synthesis could be relevant for design of coastal structures, and may change current design philosophies. The purpose of this paper is to highlight and discuss these changes and conclusions.

2. RECENT RESEARCH

Research into the four topics listed above has advanced our understanding of key physical processes and prediction methods significantly over recent years. These advances have however progressed more or less independently in each subject area, so that possible linkages have not become immediately obvious. The most recent results on the occurrence of toe scour have, however, highlighted a common feature of all four damage mechanisms, which forms the central theme of this paper—the linkage of exposure to particular breaker types, and therefore to the ratio of wave height to water depth at the structure. Wave action on Lomener Breakwater in Brittany (Fig. 2) can be seen to cause maximum exposure at mid-tide, with very violent wave breaking. At high tide, the critical wave height/depth ratio has not been reached and the high waves are mostly reflected. This behaviour is seen very clearly also on Alderney Breakwater where overtopping is often greatest at mid-tide, and was explained in relation to overtopping at Samphire Hoe.[6] In the following, the four different exposure mechanisms and their connection with breaker types are re-presented.

3. IMPACT PRESSURES

Impact pressures and impulsive loads are generated by waves breaking directly onto a coastal structure. The most advanced design method for identifying the type of wave loadings on vertical breakwaters is the parameter map developed in the MAST PROVERBS project (Fig. 3), which links a wave parameter, H_s^*, with the type of wave and wave-generated pressure—that is, either pulsating, impact or broken wave loadings—where

$$H_s* = H_{si}/h_s$$

where H_{si} is the significant wave height near the structure and h_s is the water depth in front of the berm.

Further parameters employed in Fig. 3 are: h_b, the height of the berm; B_{eq}, the equivalent length of berm (distance from centre of slope to structure); F_h, the horizontal force per m width; ρ, the density of water; g, the acceleration of gravity (9·81 m/s^3).

For vertical structures without or with a small berm in front of the wall, impact loads occur for $H_s^* > 0{\cdot}35$. No upper limit of H_s^* is given to indicate the onset of the significantly smaller broken wave loadings.

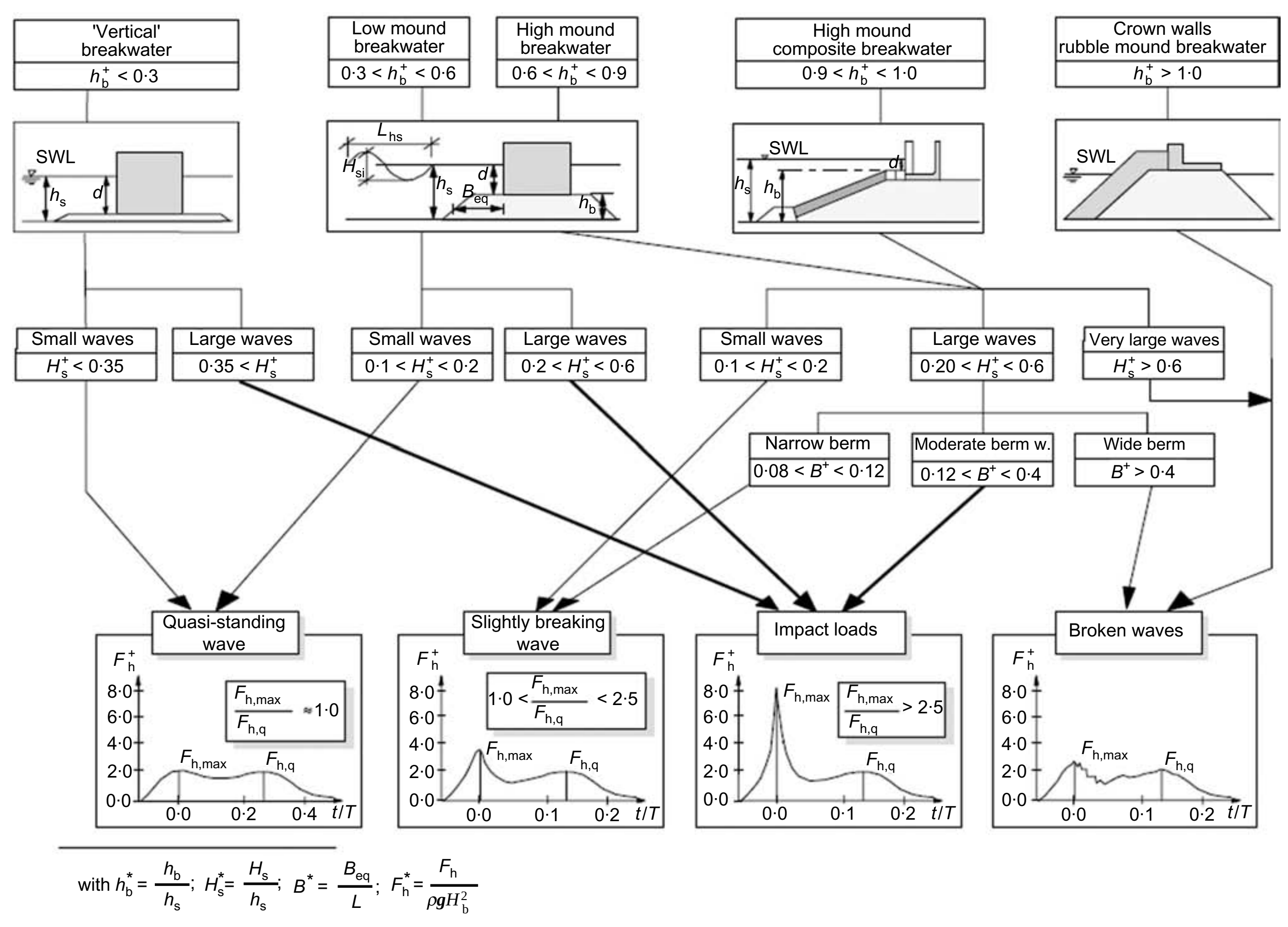

Fig. 3. PROVERBS parameter map (© A. Kortenhaus, with permission)

For composite breakwaters this method differentiates between low mound/high mound, and small waves/large waves and (in the case of high mound) between narrow, moderate and wide berm to determine whether pulsating, impact or broken wave pressures occur.

Other 'discriminators' between breaking and non-breaking wave loading conditions exist, for example the method of Calabrese and Buccino,[7] which offers a predictor of the proportion of waves breaking onto a simple or composite vertical structure. In the related area of wave overtopping, current UK guidance uses an 'impulsiveness parameter' to distinguish conditions under which the overtopping process becomes 'violent' as opposed to the 'green water' process seen under non-breaking wave conditions.[8]

In model tests of breaking wave-induced impact pressures, the sensitivity of impact pressure occurrence and magnitude to wave height variations has been demonstrated by several researchers.[9,10] Fig. 4 shows the wave impact pressures from five identical waves for each of the 32 different offshore wave heights, H_0, on a vertical wall, plotted against H_0. The water depth at the structure was 100 mm, the seabed slope 1:10, and position four is located 25 mm below MWL (this location showed the highest pressures). It can be seen that pressures increase dramatically from $H_0 > 65$ mm, when the wave is breaking right against the structure, indicating the step function in exposure from the previously reflected or pulsating wave. For $H_0 > 75$ mm, the waves break before reaching the structure and pressures are again reduced significantly.

4. DOWNFALL PRESSURES

Substantial downfall pressures generated by water masses thrown up by wave breaking/overtopping, and then falling onto the deck of a coastal structure have been demonstrated in small- and large-scale experiments.[12] Figure 5 shows the results from large-scale experiments conducted in the Large Wave Channel (GWK) in Hanover, Germany.

The simultaneous (same wave, but slight time delay) measurements of impact and downfall pressures ($\boldsymbol{P}_{\mathrm{impact}}$ and $\boldsymbol{P}_{\mathrm{down}}$, respectively) as shown in Fig. 5(a) indicate that maximum downfall pressures occur for near impacting conditions. It appears that high downfall pressures are only generated when a

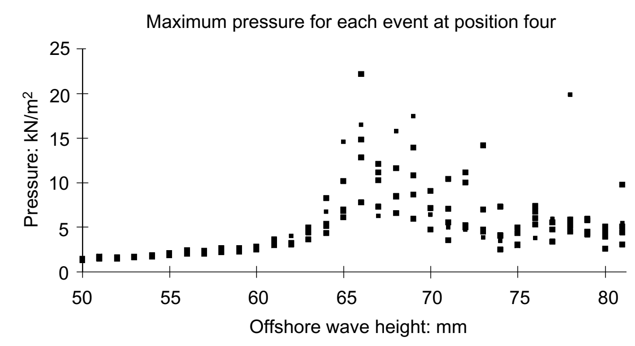

Fig. 4. Impact pressure magnitude as function of breaking wave height[11]

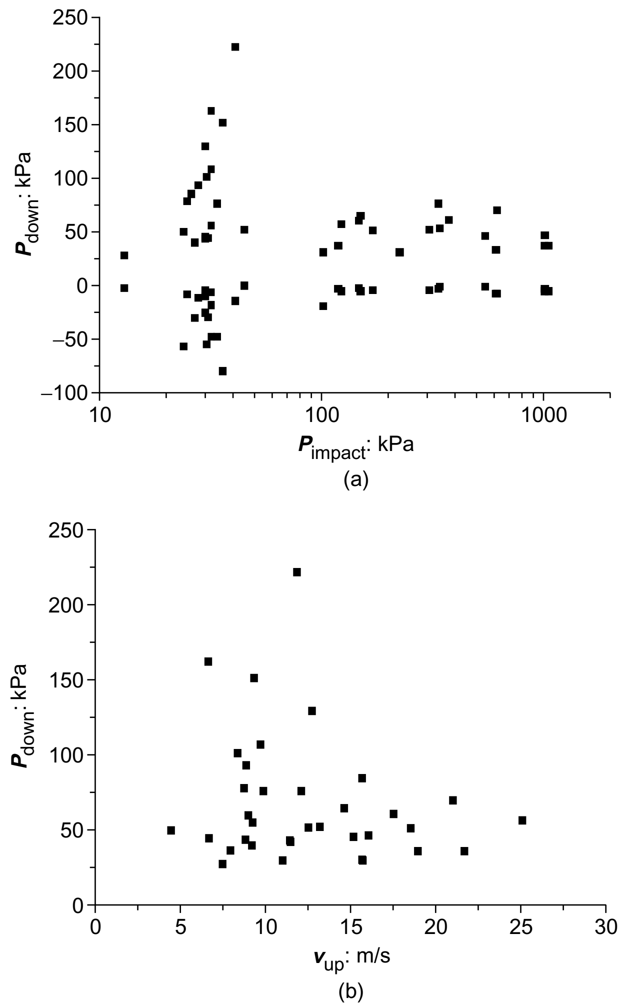

Fig. 5. Downfall pressures (large-scale experiments):[12] (a) downfall and impact pressures; (b) downfall pressures and uprush velocities

relatively compact water mass is thrown up and falls down. For lower wave heights, the uprush height is insufficient to generate large pressures. For larger wave heights, the impact itself is more violent, with higher air entrainment. This leads to increased uprush velocities and the disintegration of the uprushing water mass into spray, and causes a significant reduction in downfall pressures. The negative downfall pressures recorded in these experiments were attributed to pressure drops caused by the high horizontal velocity of the fluid particles occurring after the impact (pressures close to zero) and possibly due to cavitation (downfall pressures approaching − 100 kPa). Figure 5(b) shows the downfall pressures ($\boldsymbol{P}_{down}$) as a function of the uprush velocity, V_{up} (which is a near linear function of the wave impact pressure magnitude[12]) for a constant water depth, h_b. The negative pressures have been omitted in this analysis and therefore fewer measurement points are present. The highest downfall pressures occur for uprush velocities of 12–13 m/s, not for the maximum uprush velocities of 25 m/s, again indicating that the 'compactness' of the water mass thrown up by the wave affects the pressure.

5. OVERTOPPING

Most prediction methods for wave overtopping suggest that maximum overtopping rates occur for high waves and small freeboard/maximum water depth, h_b, at the structure, with overtopping rates decreasing with decreasing wave height. In contrast, careful examination of wave overtopping responses[2,6] has shown that the change from non-impulsive to impulsive conditions may substantially increase overtopping even when the water level is reducing. Fig. 6 gives predicted overtopping discharges as a function of water depth (x-axis) and wave heights. The overtopping discharge is determined using two formulae: one for impulsive (violent, breaking wave-induced) overtopping (for lower water levels; to the left of the chart), and one for non-impulsive (green water) overtopping (for higher water levels; to the right of the chart). The formula to be used is determined according to the h^* parameter used in UK guidance.[8] For lower wave heights (e.g. $H_S = 2{\cdot}5$, $2{\cdot}0$ and $1{\cdot}5$ m) it is striking that the curves coming from the left (impulsive conditions) have a different gradient to the curves coming from the right (green water overtopping), and a jump or switch occurs at this point (again assuming a reducing water level and coming from the right). The previously non-breaking waves start to break, giving (for these parameter combinations) a significant step-up in overtopping discharge. Overtopping rates are therefore strongly determined by the occurrence of violent wave breaking at the structure.

It should be noted that the dashed lines in Fig. 6 are extrapolations of prediction tools outside their validated ranges. These are not large extrapolations, however, and even with some uncertainty, the existence of a significant switch between the two sets of lines remains clear.

6. TOE SCOURING

Toe scouring, namely the formation of a scour hole at the toe of a structure which may lead to undermining and failure, has until recently been attributed to

(*a*) wave reflections which increase wave heights, velocities and turbulence
(*b*) currents trained along a seawall
(*c*) cross-shore flows under the base of the structure and vertical flows through the beach which increase mobility.

Maximum scour depths were assumed to occur at the height of the storm, but it was generally accepted that they tend to fill in (at least partially) during the receding period. This assumption could, however, not be confirmed since measurements under storm conditions were impossible. As most toe scour studies were conducted for a particular structure or location and consequently had limited parameter ranges, no complete view of the scouring process as a function of wave height has been reported until very recently. In recent physical model tests, it was found that maximum toe scour depths, S_t, occur for breaking wave conditions, namely plunging breakers.[13] Fig. 7 shows the ratio of toe scour depth and significant wave height, S_t/H_s, plotted against relative water depth at the structure, h_b/L_m, where L_m is the deep water wavelength based on the mean period, T_m. The experimental results and field measurements ('Blackpool data') indicate that water thrown into the air by the impact then falls down, exacerbating the scour hole right at the structure toe. For smaller wave heights and pulsating conditions, flow velocities at the toe are minimal and an erosion hole forms at the quarter wave length distance; and material is deposited at the toe. Larger waves, or shallow water depth, lead to less fully-developed breakers and the potential for sediment accretion at the toe.

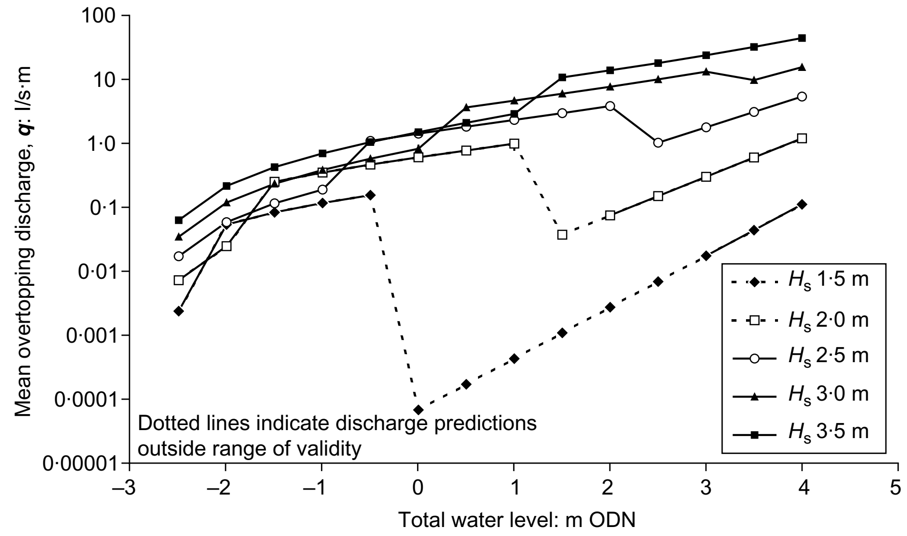

Fig. 6. Overtopping discharge as a function of wave height and water depth at the structure[2]

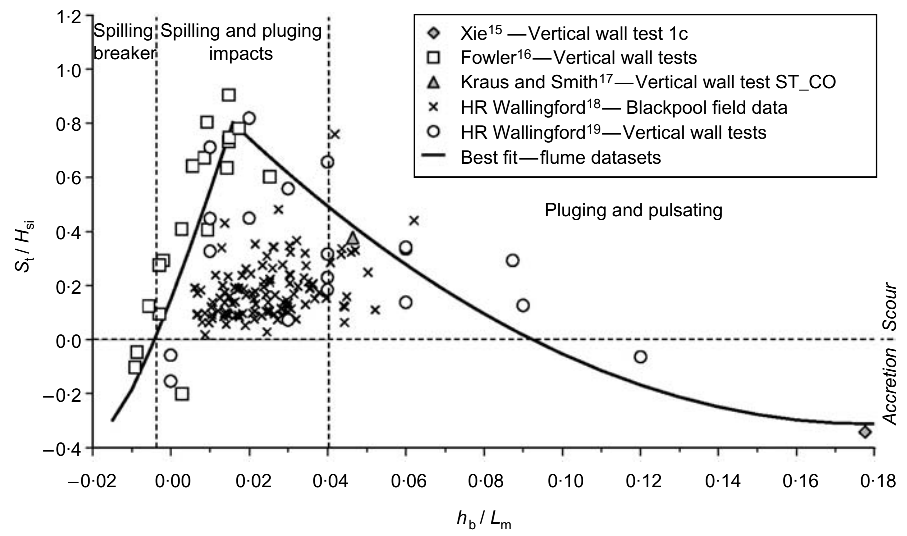

Fig. 7. Non-dimensional toe scour depth at a vertical wall as a function of breaker type—comparison of mid-scale flume data and Blackpool field results[14–19] (©A. Pearce, with permission)

$H_s^* \leq 0{\cdot}625$. The graphs indicate that H_s^* is also a function of seabed slope and wave steepness,[20] assertions supported in the literature.[21,22] These effects require further investigation, particularly for steeper bed slopes.

These considerations suggest that the maximum exposure a structure will experience during a storm is a function of the breaker type, and therefore a function of the combined probability of wave height and water level, and hence of the proportion of impacts and their intensity.

Simplifying, severe exposure conditions may therefore exist for a window of $0{\cdot}35 < H_s^* < 0{\cdot}625$ in which the impact pressure, downfall pressures and overtopping, as well as toe scour, all occur, possibly simultaneously. The duration of this window determines the degree of exposure. For conditions outside the window, the potential for violent breaking responses will be significantly reduced.

In order to illustrate the effect of tidal elevation of the duration of the exposure window, a theoretical study was performed with a water depth $h_b = 1{\cdot}50$ m, a wave height $H_{si} = 0{\cdot}80$ m, an assumed storm profile of 4 h ramp-up, 4 h constant wave height and 4 h ramp-down and two different tidal ranges (Fig. 8). The 'exposure window', defined as the period of time when $0{\cdot}35 < H_s^* < 0{\cdot}625$, decreases from 6·6 h for a tidal range of 0·5 m, to 4·6 h for 1·0 m tidal range and 1·4 h for 2·0 m tidal range. The duration of the critical wave height to water depth ratio shortens as the tidal range increases, indicating that the combined probability of critical conditions is reduced. Fig. 8(b) and (c) also indicate that critical conditions need not necessarily occur during the height of the storm; breaking wave conditions can also exist during ramp-up or ramp-down of storm wave heights, for example Fig. 8(c) for $T = 9{\cdot}9$ to $10{\cdot}4$ h. The theoretical study therefore illustrates the effect of the combined probability of wave height and water depth for the occurrence of maximum exposure; the probability reduces with increasing variability of the parameters wave height and water level.

7. SYNTHESIS

The four different exposure types presented all occur under near-breaking and fully-developed breaking conditions; with maxima for different responses/exposure types occurring for somewhat different conditions (e.g. near-breaking waves give rise to maximum downfall pressures whereas fully-developed breakers result in maximum impact pressures, overtopping and toe scouring). Breakers at a vertical wall are a depth-limited phenomenon and occur for $H_s^* > 0{\cdot}35$, as was demonstrated in a series of experiments,[1] but disappear when the breaker height increases such that the breaking point moves seaward, leading to broken wave impacts at the wall. Little direct information is available on the occurrence and height of broken waves at vertical walls. It might therefore be assumed that broken wave impacts could occur for most of the incoming waves when the average wave height, H_{av}, exceeds the water depth at the structure. With $H_s \approx 1{\cdot}6 H_{av}$,[20] this gives an upper limit for the occurrence of wave impacts of

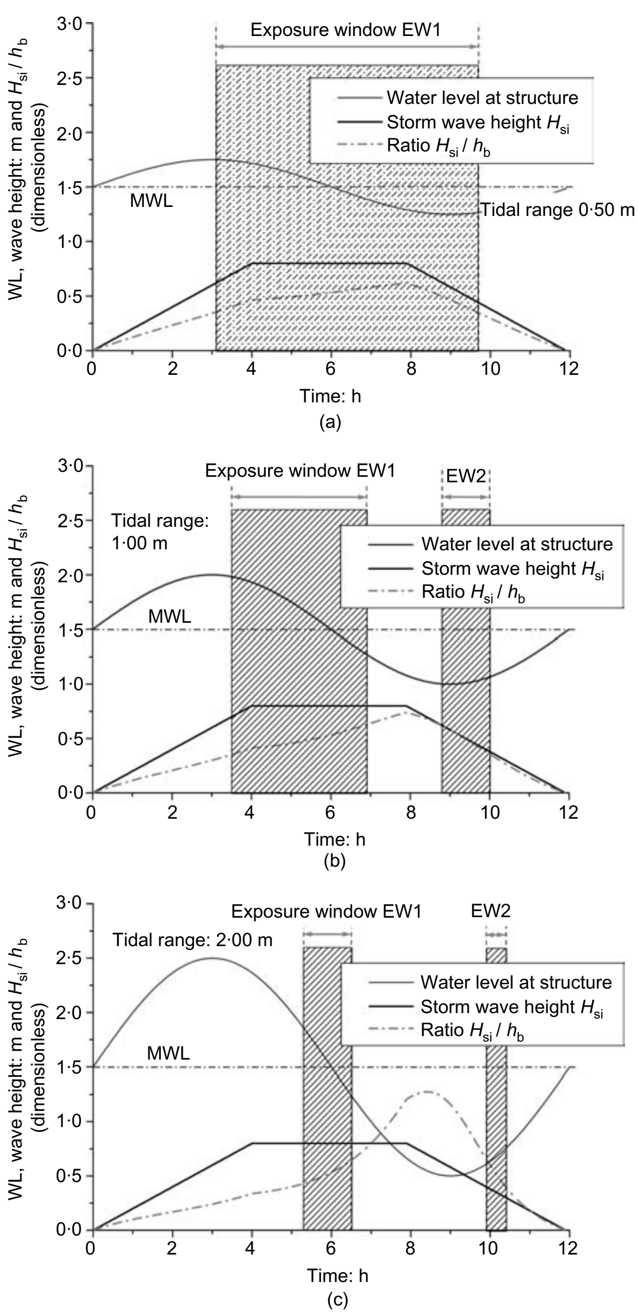

Fig. 8. Exposure windows for two different tidal ranges: (a) tidal range 0·50 m, window duration 6·6 h; (b) tidal range 1·00 m, window duration 4·6 h; (c) tidal range 2·00 m, window duration 1·4 h

8. DISCUSSION

The authors suggest that, assuming that storms have a certain characteristic wave height distribution (ramp-up, flat, ramp-down), the existence of an exposure window means that extreme exposure is very much dependent on tidal levels, and the temporal relationship of storm and tidal cycles. Large tidal variations mean that the maximum exposure window becomes short, so that although very violent storm conditions may prevail, the exposure duration itself is limited. Small tidal variations on the other hand can lead to exposure windows being open for prolonged periods, therefore maximising the exposure. This might explain why storm damage to coastal structures can occur frequently in the Mediterranean Sea, where fetch lengths and storm durations are significantly smaller than those in the North Atlantic but very small tidal variations prevail.[23]

The design of vertical walls and related structures should therefore consider exposure durations through the combined probabilities of storm characteristics and variations in water level at the structure, leading to different degrees of exposure for structures subjected to the same wave condition but different tidal ranges.

The same considerations should be included in the design of physical model tests. It may be more important to include variations of tidal levels (even if small) to ensure that the degree and/or duration of exposure conditions are reproduced rather than conducting experiments with large numbers of waves. This might require model tests to reproduce both storm profiles (see the discussion[24]) and appropriate tidal variations.

At the moment, however, it is difficult to establish clear boundaries for actual exposure windows since, for example, the point of transition from plunging wave impacts to spilling/broken wave impacts cannot clearly be defined. The effects of seabed slope on breaker type and breaking point for situations with a vertical structure have also still to be investigated thoroughly.

9. CONCLUSIONS

Vertical coastal structures are often exposed to violent wave action. Recent research has shown that wave impact pressures, toe erosion and overtopping/overtopping-induced pressures are all caused by plunging or near plunging breakers. Since wave breaking is a depth-influenced phenomenon, the exposure of a coastal structure to extreme wave action depends not only on wave characteristics but also on the water level or, in other words, on the combined probability of wave height and tidal elevation plus surges. A theoretical study has shown here that, for an idealised storm, exposure increases for decreasing tidal variation. This may explain the extreme exposure of coastal structures in areas with small tidal variations, as witnessed by frequent and severe damage, and could have consequences for the design of physical model tests and other forms of analysis.

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